Heatshield for Extreme Entry Environment Technology (HEEET) Development Status

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  - Jacobs Technology Inc.
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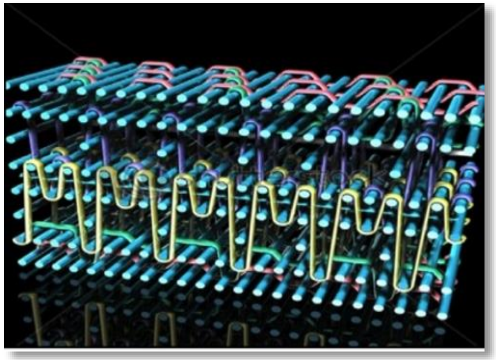
- **Neerim Corp:**
  - Peter Gage
- **NASA ARC, AEDC, LaRC and LHMEL test facilities and their crews**
- **Bally Ribbon Mills:**
  - Weaving
- **Fiber Materials Inc. (FMI)**
  - Forming/Resin Infusion/Machining: Acreage and Gap Fillers

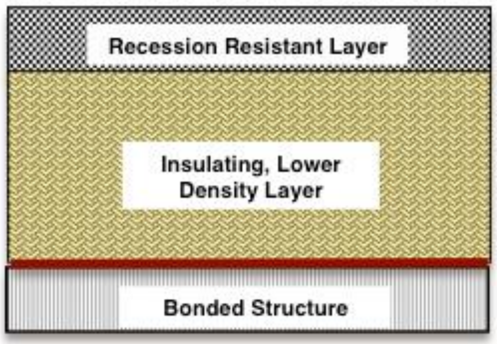
Outline

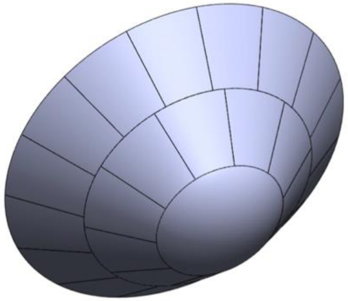
- **Introduction to HEEET Project**
- **HEEET Material: Dual Layer 3D Woven TPS Material**
- **TPS Sizing: Saturn and Venus**
- **Engineering Test Unit Design: Saturn Probe**
- **HEEET Manufacturing/Integration**
- **Thermal Testing**
- **Structural Testing**
  - LHMEL 4pt Bend (Entry Performance)
  - Engineering Test Unit (ETU)
- **Schedule**
- **Deliverables**
- **Roles and Responsibilities – HEEET Team support for Proposal Teams**
- **Summary**

Heatshield for Extreme Entry Environment Technology (HEEET) Project

- **Goal: Mature HEEET system in time to support New Frontiers – 4 opportunity (mission infusion)**
  - Target missions include Saturn Probe and Venus Lander
  - Capable of withstanding extreme entry environments:
    - Peak Heat-Flux >> 1500 W/cm^2; Peak Pressure >> 100 kPa (1.0 atm)
  - Scalable system from small probes (1m scale) to large probes (3m scale)
  - Sustainable – avoid challenges of C fiber availability that plague Carbon Phenolic
  - Development of the whole Integrated system, not just the material (includes seams)
    - Culminates in testing 1m Engineering Test Unit (ETU)
      - Integrated system on flight relevant carrier structure

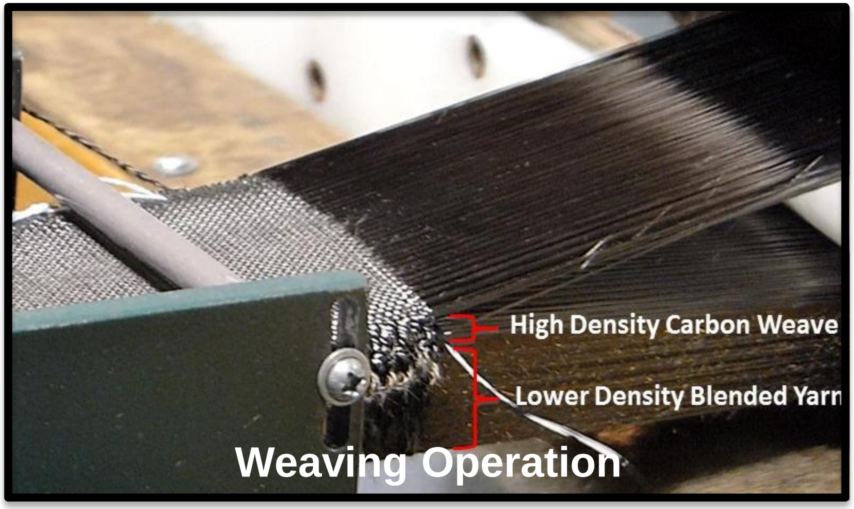


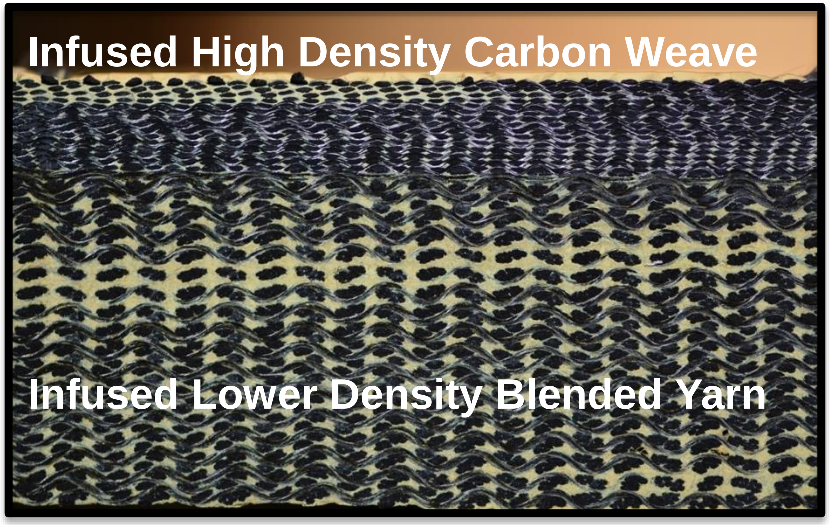




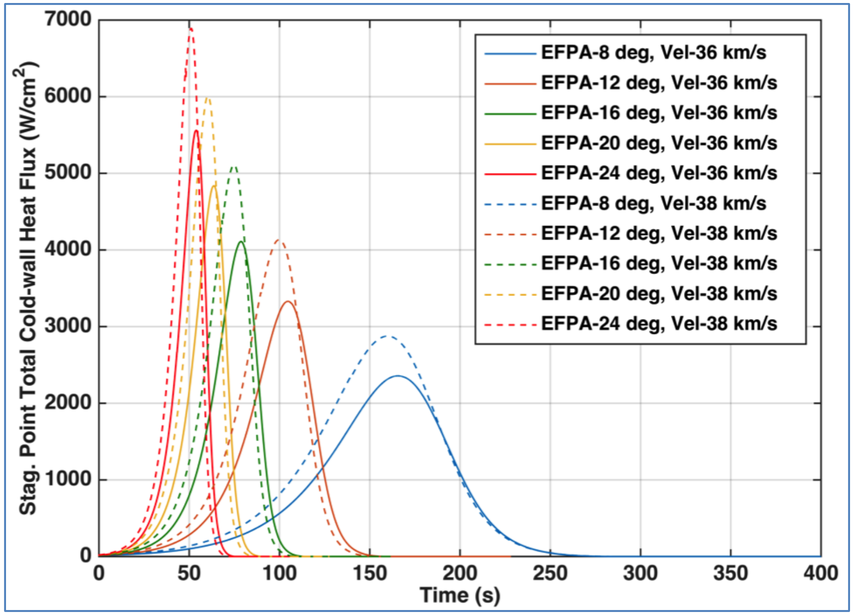
HEEET Material

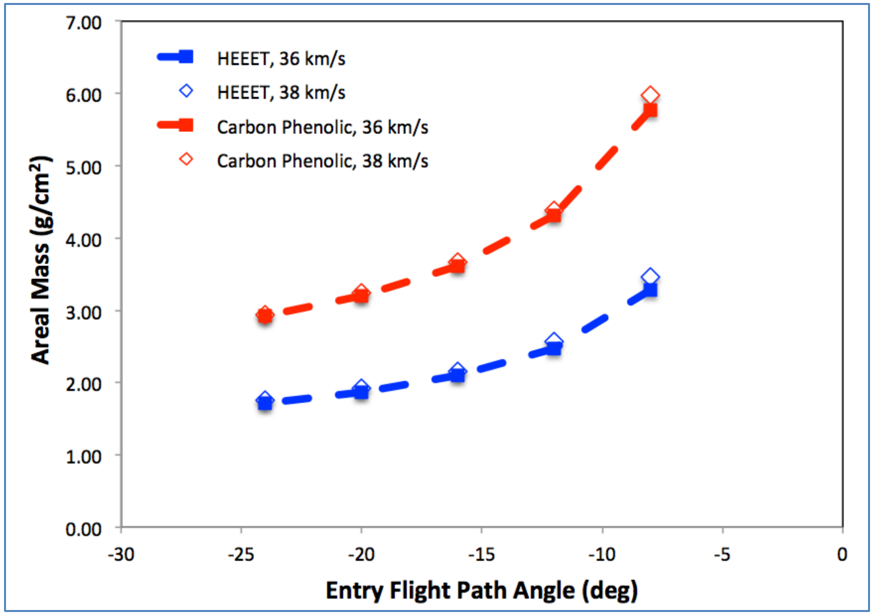
- **Dual-Layer 3-D woven material infused with low density phenolic resin matrix**
  - Recession layer
    - Layer-to-layer weave using fine carbon fiber - high density for recession performance
  - Insulating layer
    - Layer-to-layer weave: blended yarn - lower density/lower conductivity for insulative performance
- **Material Thickness:**
  - 2.1in (5.3 cm) thick material [0.6in (1.5cm) recession layer, 1.5in (3.8cm) insulating layer)]
- **Material Width:**
  - Currently manufacturing 13in (33cm) wide material
  - Weaving scale-up in progress for 24in (61cm) wide material
  - Weaving limitations drive need for a tiled system





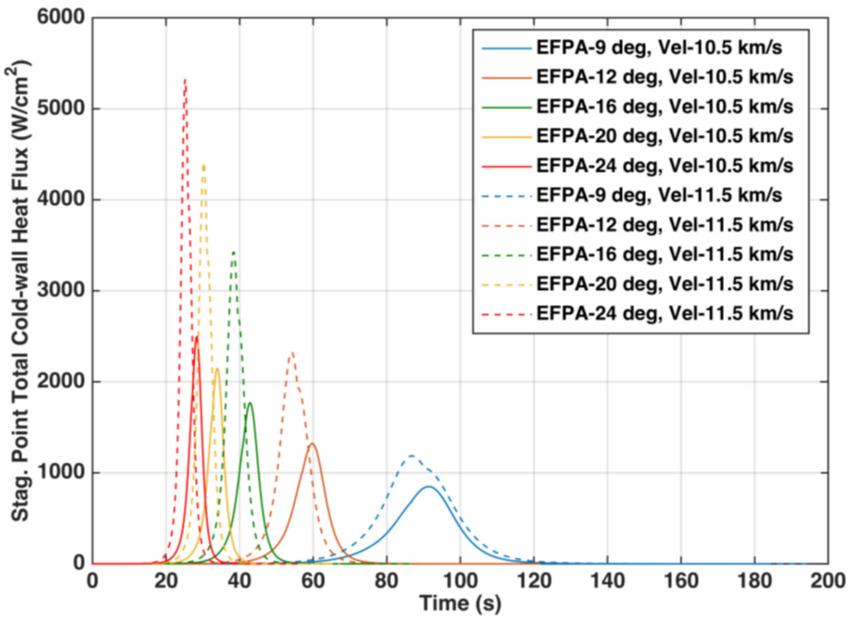
Saturn Entry Probe
Areal Mass Comparisons

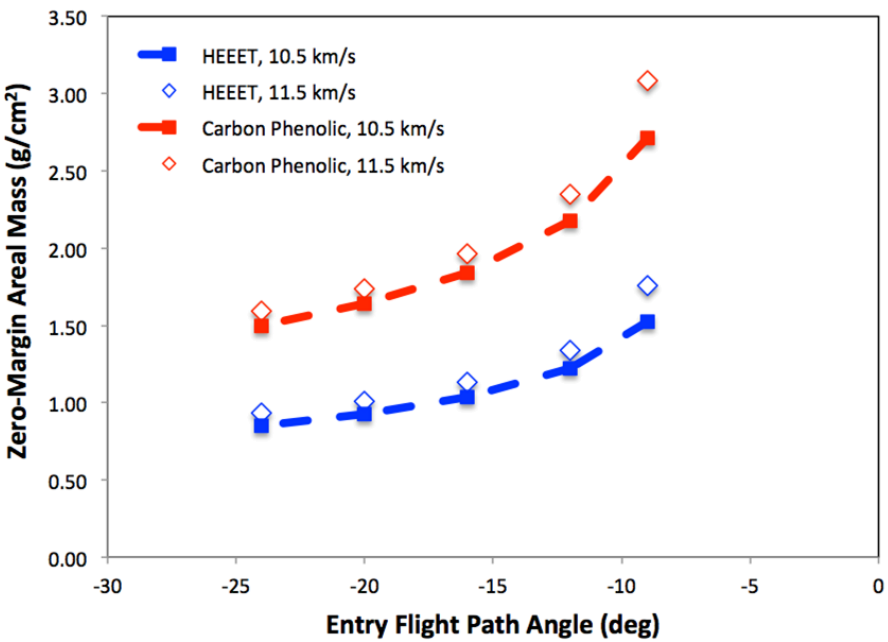




- Stagnation point analysis
  - 200 kg, 1-meter diameter, 45-deg sphere cone, nose radius of 25 cm, Ballistic Coeff = 252 kg/m^2
  - Inertial entry velocities of 36 and 38 km/s. Inertial entry flight path angles between -8 and -24 deg
  - Equatorial entry in the eastern (prograde) direction
- Saturn entry is extreme - very high heat-flux and pressure and long flight duration results in extreme heat-load (75 - 250 kJ/cm^2)
- Areal mass of the 2-layer (HEEET) system has the potential for > 40% mass savings relative to heritage Carbon Phenolic
  - Sizing results are for zero margin utilizing preliminary thermal response model

Venus Entry Probe
Areal Mass Comparisons



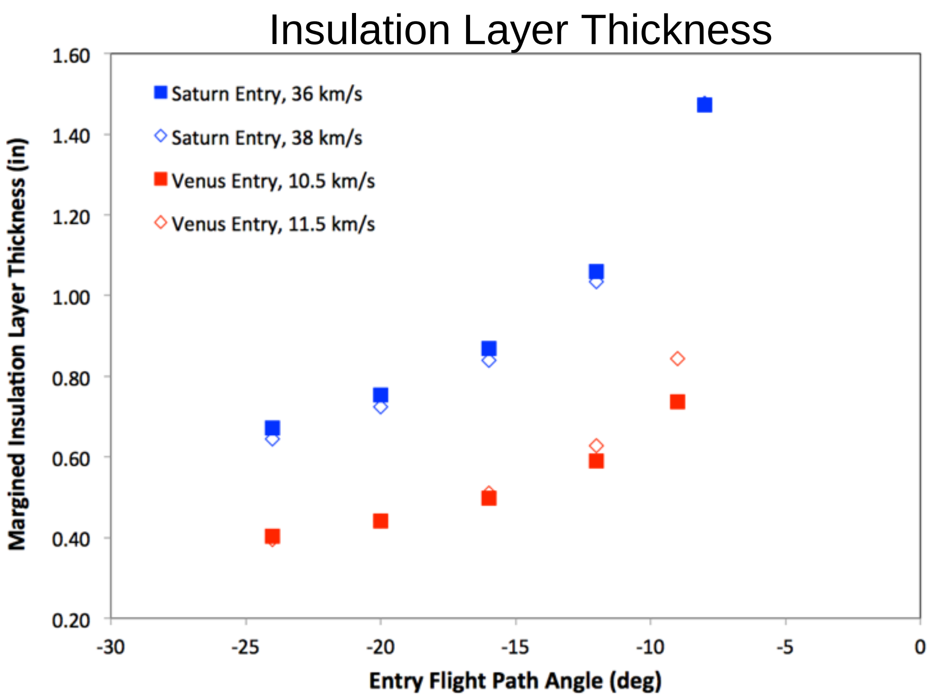


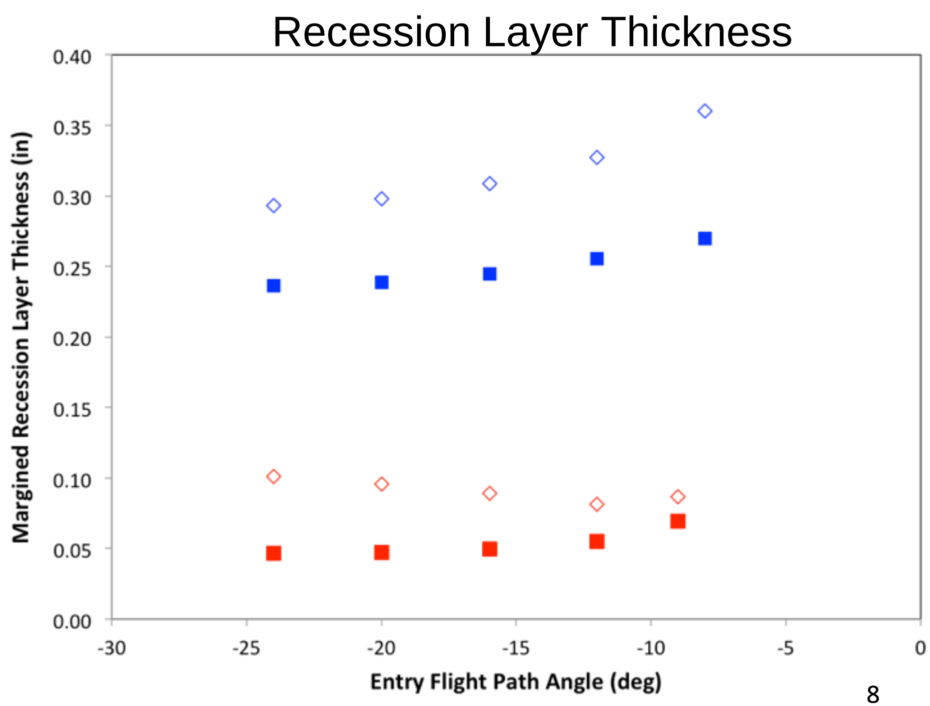
- Stagnation point analysis
  - 2750 kg, 3.5-meter diameter, 45-deg spherecone, nose radius of 87.5 cm, Ballistic Coeff = 272 kg/m^2
  - Inertial entry velocities of 10.8 and 11.6 km/s. Inertial entry flight path angles between -8.5 to -22 deg
- Venus (12-36 kJ/cm^2) has lower heat loads than Saturn (75-250 kJ/cm^2)
- Areal mass of the 2-layer (HEEET) system has the potential for > 40% mass savings relative to heritage Carbon Phenolic
  - Sizing results are for zero margin utilizing preliminary thermal response model
- Mass efficiency of HEEET may enable shallower EFPA than feasible with CP, resulting in lower g – loads

HEEET Thickness for Reference Missions

Missions to Saturn generally require a thicker TPS than Venus missions due to higher heat load

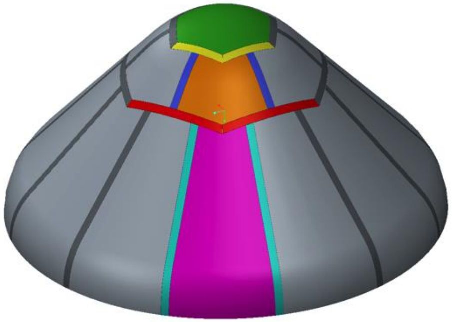
- Recession layer thickness for Saturn missions is 0.2-0.4 inches while for Venus missions is 0.05-0.15 inches
  - Actual recession is 2/3 of the margined recession layer thickness
- Insulation layer thickness for Saturn missions is 0.6-1.4 inches while for Venus missions is 0.4-0.8 inches
- Total thickness: Saturn = 0.9 – 1.7 inches; Venus = 0.5 – 0.9 inches
- Added margins accounting for trajectory and aerothermal uncertainties may increase the required thickness
- Differences in atmospheric composition (Venus CO_2 vs Saturn H_2/He) is accommodated via modeling
  - Current arcjet test capability at extreme entry environments is limited to air



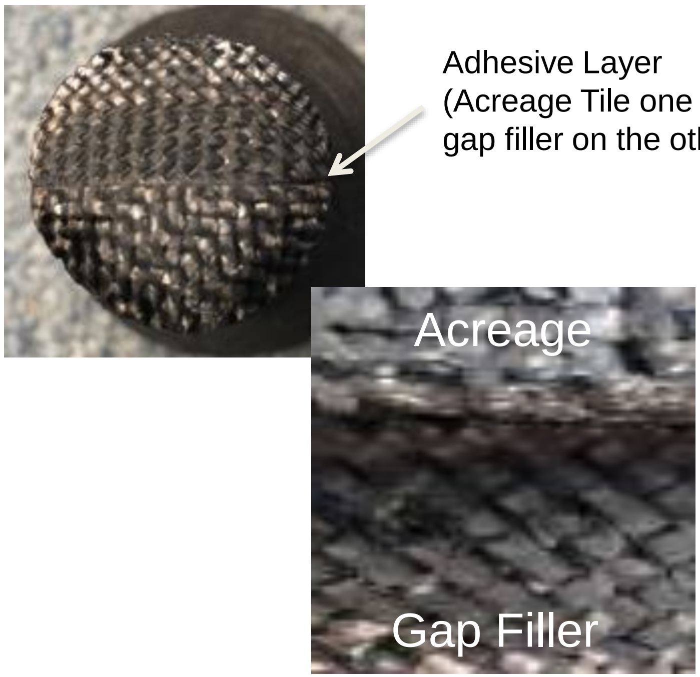


HEEET Gap Filler

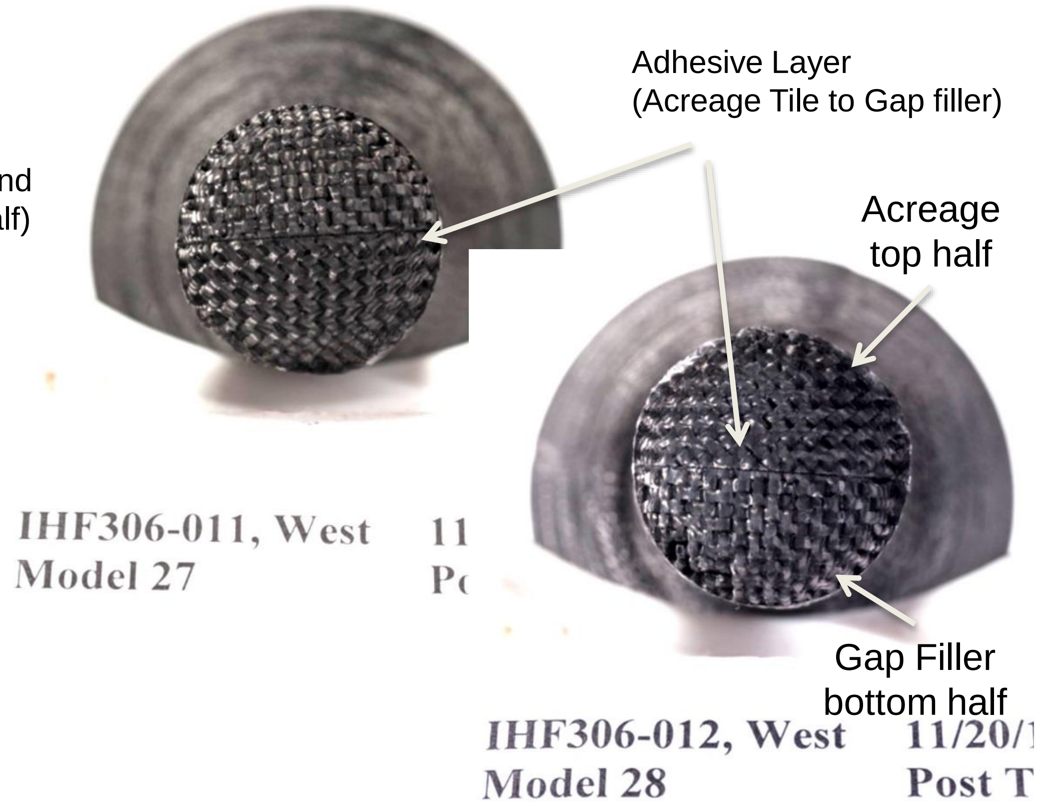
- **Weaving size limitations require use of a tiled TPS**
  - Acreage Tiles
  - Gap Fillers
- **Gap filler between tiles performs two primary functions:**
  - Provide structural relief for all load cases
    - Achieved by relatively high compliance of gap filler compared to acreage tiles
    - Required strain accommodation by gap filler is driven in part by stiffness of carrier structure (coupled design)
  - Provide an aerothermally robust joint, “aerothermally monolithic seam”
    - Recession performance in family with acreage material
    - Achieved by:
      - Gap Filler composition similar to acreage material
      - Very thin adhesive widths between gap filler and acreage tiles



HEEET Seam Aerothermal Performance (~7000 W/cm² and 5 atm)



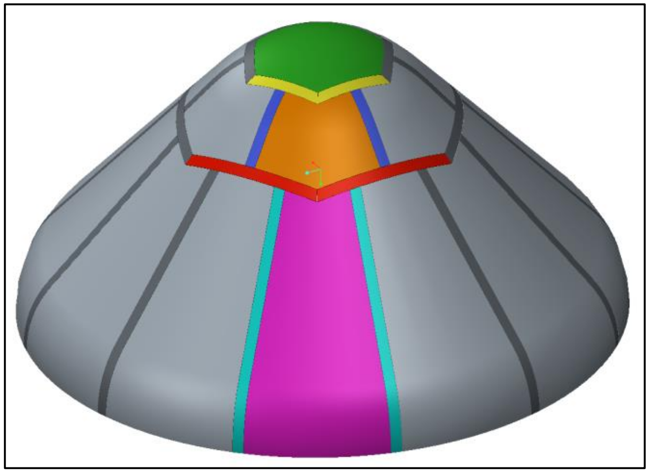
Adhesive Layer
(Acreage Tile one half and gap filler on the other half)



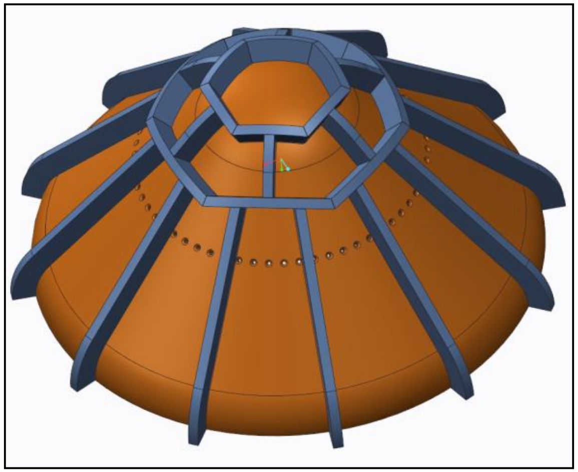
- **IHF 3” nozzle arcjet testing (~ 7000 W/cm² and 5 atm) of HEEET seam designs completed**
- **Feasibility of seam design demonstrated**
- **Test articles showed aerothermally “monolithic” behavior**
  - **Seam and acreage showed similar recession behavior**

HEEET 1m Engineering Test Unit (ETU) Saturn Probe Reference Mission

ETU Architecture & Part Nomenclature



Complete ETU



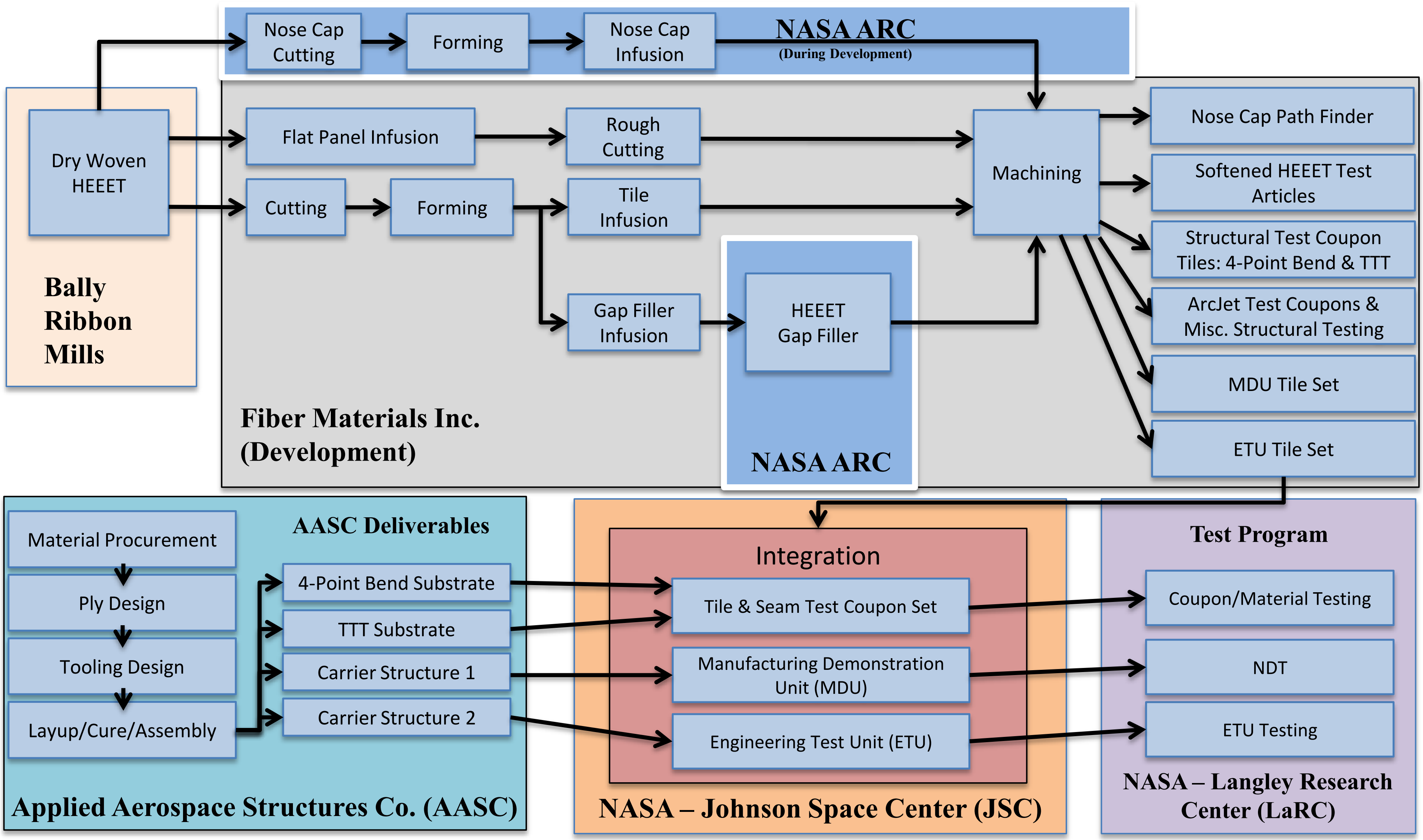
ETU – Gap Fillers Only

ETU – Acreage Tiles Only

Tiles
- **Shoulder Radius: 5.65” OML**
- **Tile Thickness (1.65”)**

Tile Type	Tile Color	Tile Quantity for 1x Tile Set
Nose Cap		1
Inner Circumferential Gap Filler		6
Inner Radial Gap Filler		6
Inner Tile		6
Outer Circumferential Gap Filler		6
Outer Radial Gap Filler		12
Outer Tile		12

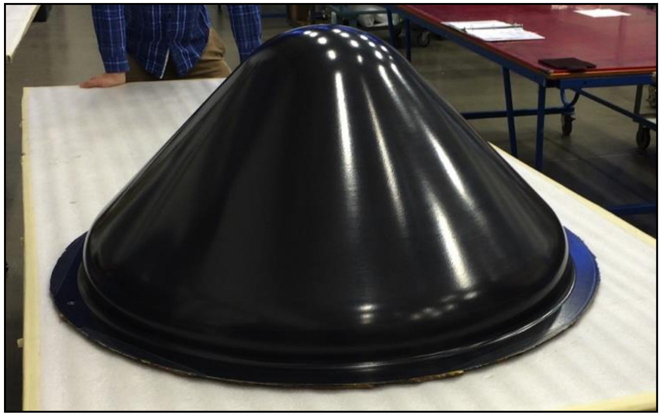
HEEET Manufacturing Overview



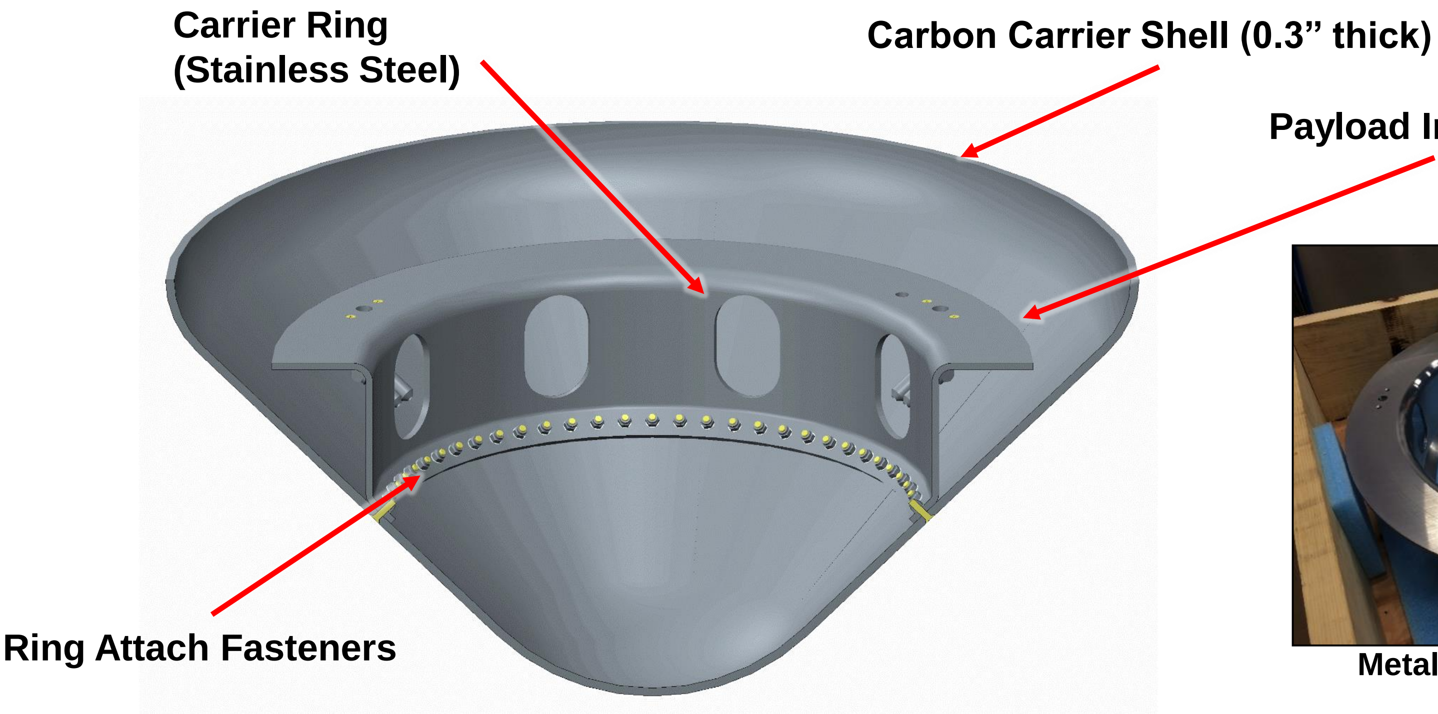
MDU/ETU Carrier Structures

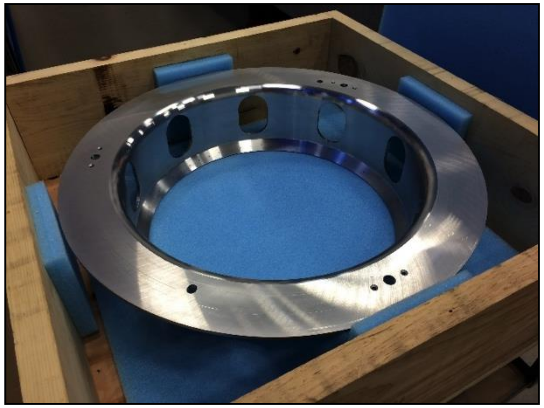
Carrier Structure Vendor - AASC

- Flat substrates for structural testing have been delivered
- Both PMC Aero Shells complete, ready for assembly



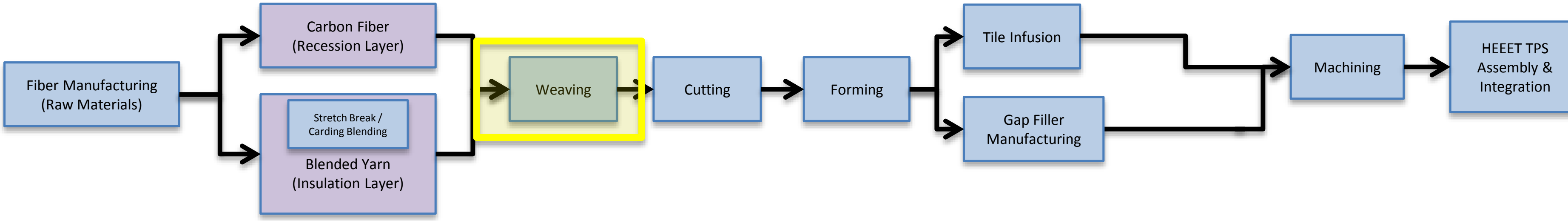
Aero Shell – After Cure



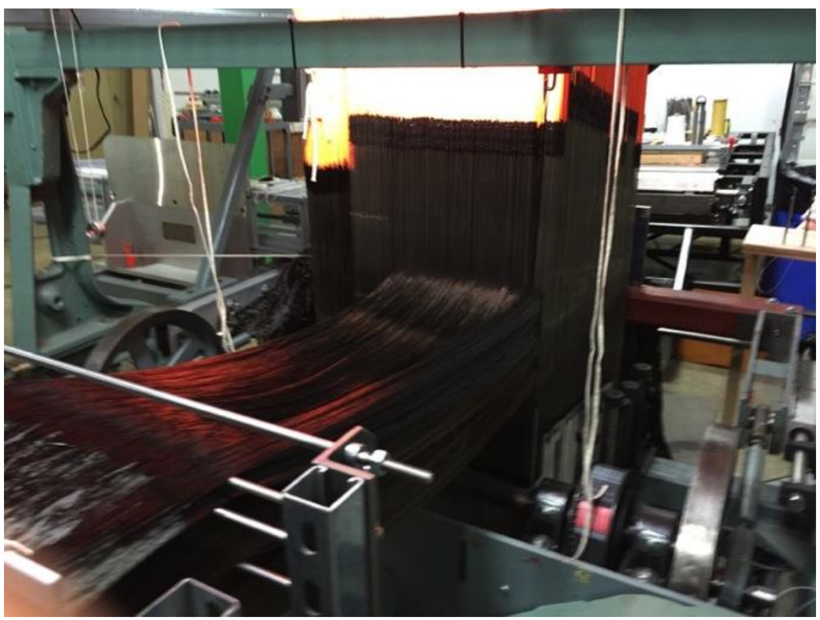


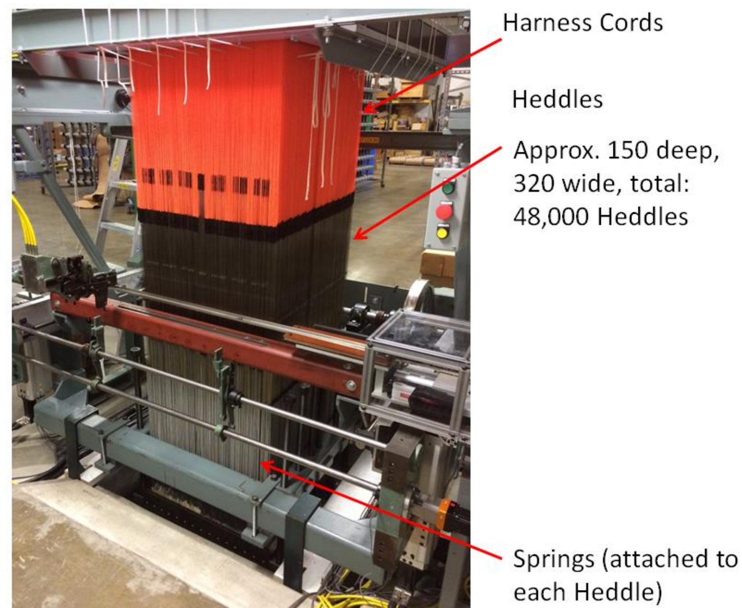
Metallic Substructure Ring

Weaving

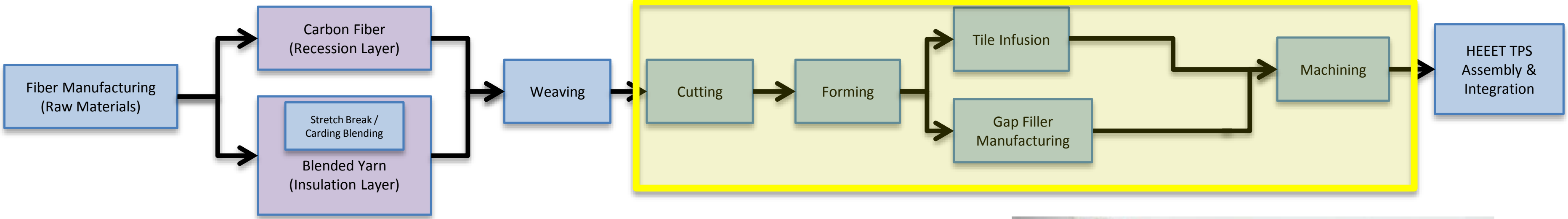


- **Weaving:**
  - BRM has completed weaving 125+ ft of 13” wide x 2.1” thick material
    - Increase in capability from 6” width x 1” thickness
  - In process of scaling up to 24” wide x 2.1” thick material

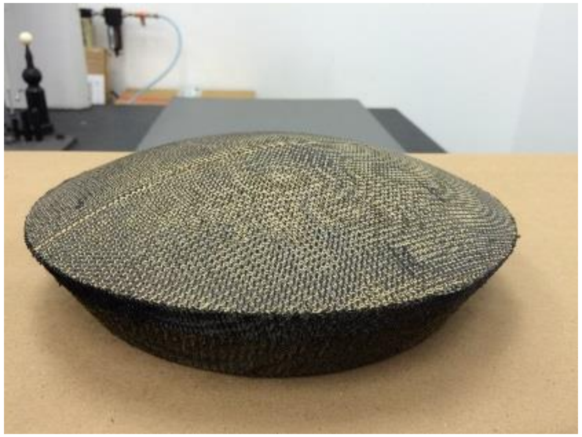




Acreage Tile and Gap Filler Manufacturing



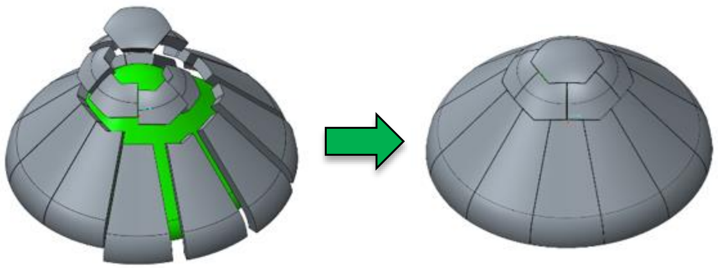
- **Acreage Tile and Gap Filler Manufacturing**
  - FMI has completed vessel upgrade required for HEEET infusion
    - Vessels utilized for PICA infusion using similar process
  - FMI has completed forming and infusion of first vessel run of tiles for 1m development unit
  - FMI has demonstrated machining capability on HEEET nose cap



HEEET Integration Approach

Step 1 – Acreage Tile Installation

- Oversized Acreage Tiles bonded to carrier structure



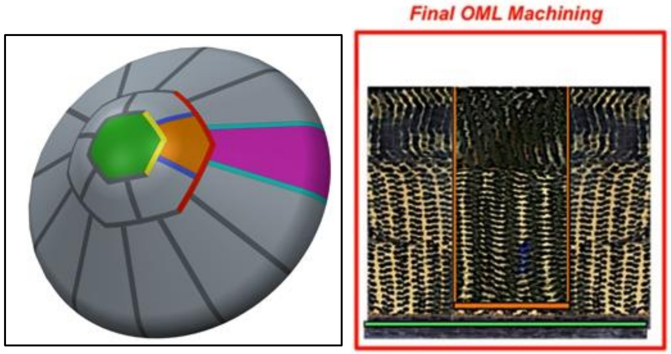
Step 2 – Channel Routing

- Route Channels Along Tile to Tile Joints

Step 3 – Gap Filler Integration

Step 4 – Final OML Machining

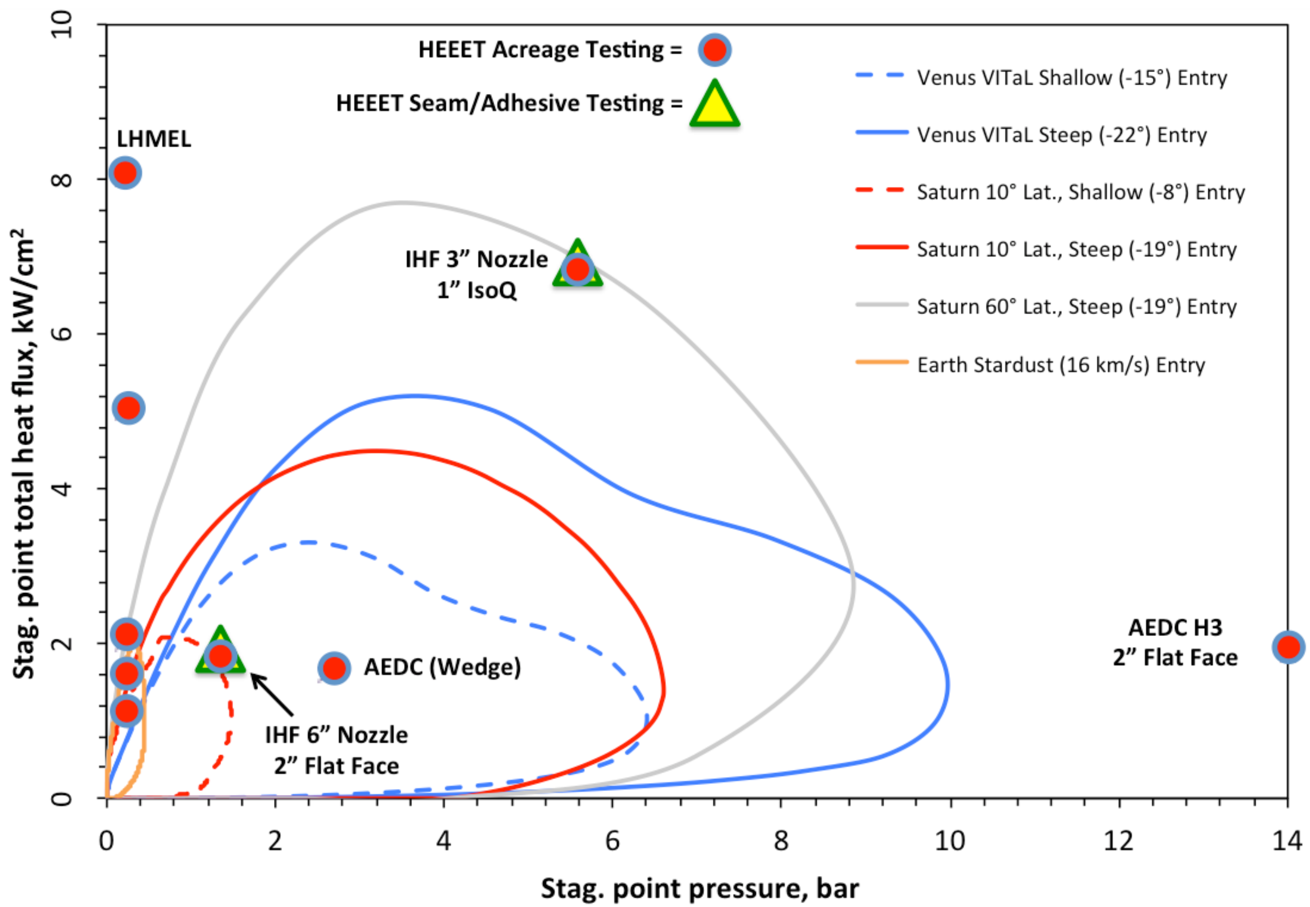
- Final Machining of OML and Shoulder Edge



Mission Relevant Heat Flux and Pressure Environment Testing

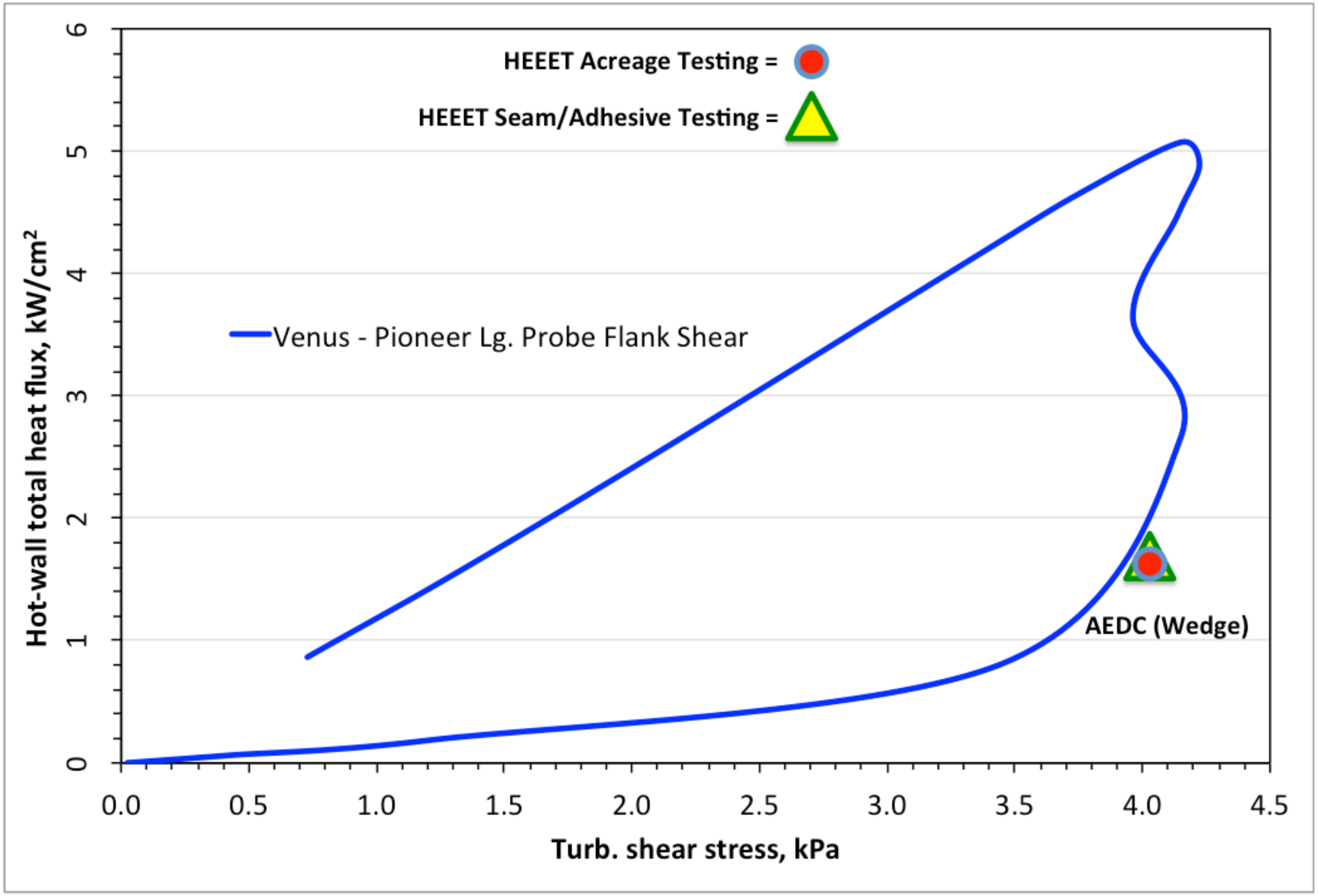
- **Stagnation point environments from Venus, Saturn and Earth entry missions**

  - High latitude Saturn entry has the highest heat flux
  - Venus steep entry has the highest surface pressure loading
  - Saturn missions have the highest heat load (TPS thickness)



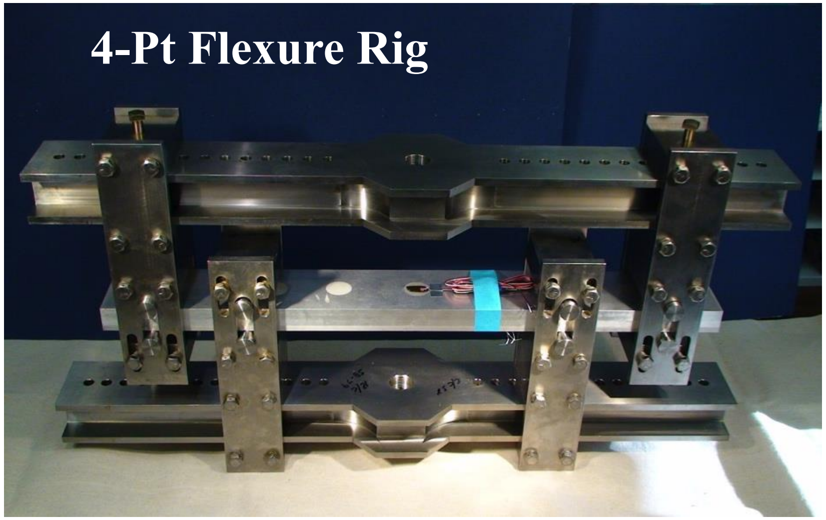
Mission-Relevant Shear Environment Testing

- **Venus Missions**
  - PVLP max shear is ~4,000 Pa
  - AEDC H3 almost bounds PVLP flank shear peak (however at lower heat flux)
- **Saturn Missions**
  - Max shear for Saturn missions ranges from 1,500 Pa to 3,000 Pa for low-latitude entry
  - Max shear happens at shoulder where flow turns



Structural Testing

- **Element, subcomponent, component and subsystem level testing are being performed to verify the structural adequacy of the ETU**
  - ETU design assumes a 1m Saturn Probe mission
  - Analytical work will be used to evaluate vehicles > 1-meter diameter (Venus)
- **Element Level Testing:**
  - Recession and Insulating Layers
  - -175F – RT – 350+F
  - Warp, Fill, Thru The Thickness (TTT)
  - Tension, Compression and Shear
- **Sub-Component Level Testing:**
  - Seam Tension Testing
  - TTT Tension Test: TPS Bonded to Carrier
    - Verify failure occurs in Insulating Layer first
  - 4pt Bend Testing
    - Acreage, seams, curved specimens
  - LHMEL 4pt Bend Testing
    - Seam structural performance during entry phase
  - Pyroshock test will be performed at the coupon level
- **ETU Testing**



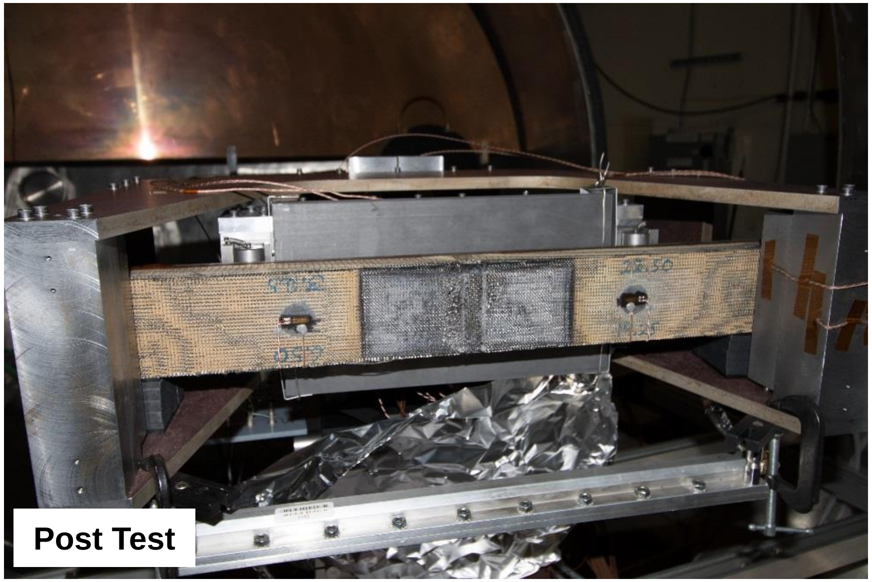
Structural Performance During Entry

- **Tiled concept requires combined thermal-structural testing.**
  - The LHMEL facility provides the ability to rapidly test various flexural configurations in a combined thermal-structural environment.
- **Entry is the most critical load case for the HEEET system, and is also the most challenging project requirement to verify.**
  - During entry the two anticipated failure modes of the seam are:
    - The sudden failure of adhesive in the recession layer, which results in a crack propagating through the remaining adhesive in the insulative layer
    - The remaining adhesive that is uncharred and able to carry load is insufficient, which results in a disbond between tiles
  - Ground based testing is required to:
    - Understand entry failure modes
    - Validate thermal-structural models
    - Demonstrate seam capability under combined thermal-structural environments.

Lev. 3 Req't #	Description
3.7	An assembly of acreage TPS material with seams onto a relevant substructure shall survive base deflections to (mission specific) magnitude and distribution during entry.

LHMEL 4pt Bend Testing

- Test Configuration:
  - Heat Flux Nominally 200 W/cm^2
  - Spot size covered a rectangular area 7” wide by 3” high
  - Target plane for requested spot size was just inside the outer load points of the HEEET TPS 4 Point Bend Test Fixture
  - 7x9-foot vacuum chamber was pumped down to 1 torr, held for 1 minute, and back filled with active nitrogen purge and chamber pumping to a pressure between 300 and 500 torr
  - 12 inch knife edge nitrogen flow across the sample face to prevent beam blockage due to ablation products


Post Test

7’x9’ LHMEL II Vacuum Chamber

ETU Testing

Engineering Test Unit (ETU) Testing Overview

- MDU and ETU Carrier Structure Proof tests to serve as precursor to ETU testing and Static Mechanical testing
- Testing to focus on random vibration (launch/ascent), thermal vacuum (on orbit/transit), static mechanical (entry), and pyroshock (separation) tests
- ETU tests planned for NASA Langley Research Center

MDU Carrier Structure Proof Test
ETU Carrier Structure Proof Test
Pre-Integration

⇓

Integrate TPS on Carrier Structure

NDE (CT)

⇓

Random Vibration

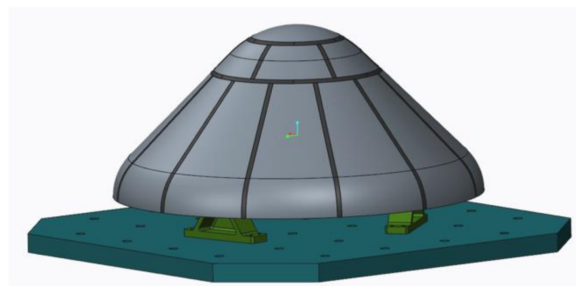
⇓

Thermal-Vacuum

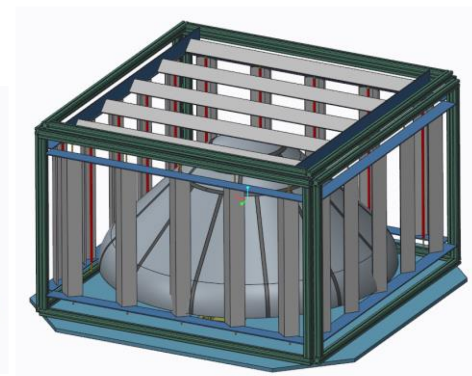
⇓

Static Mechanical

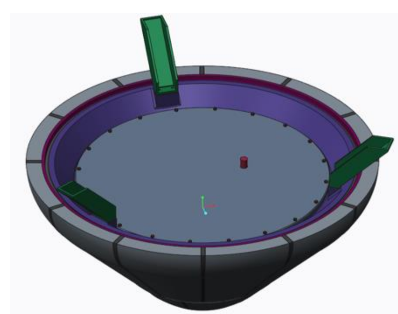
NDE (CT)



Vibration Test



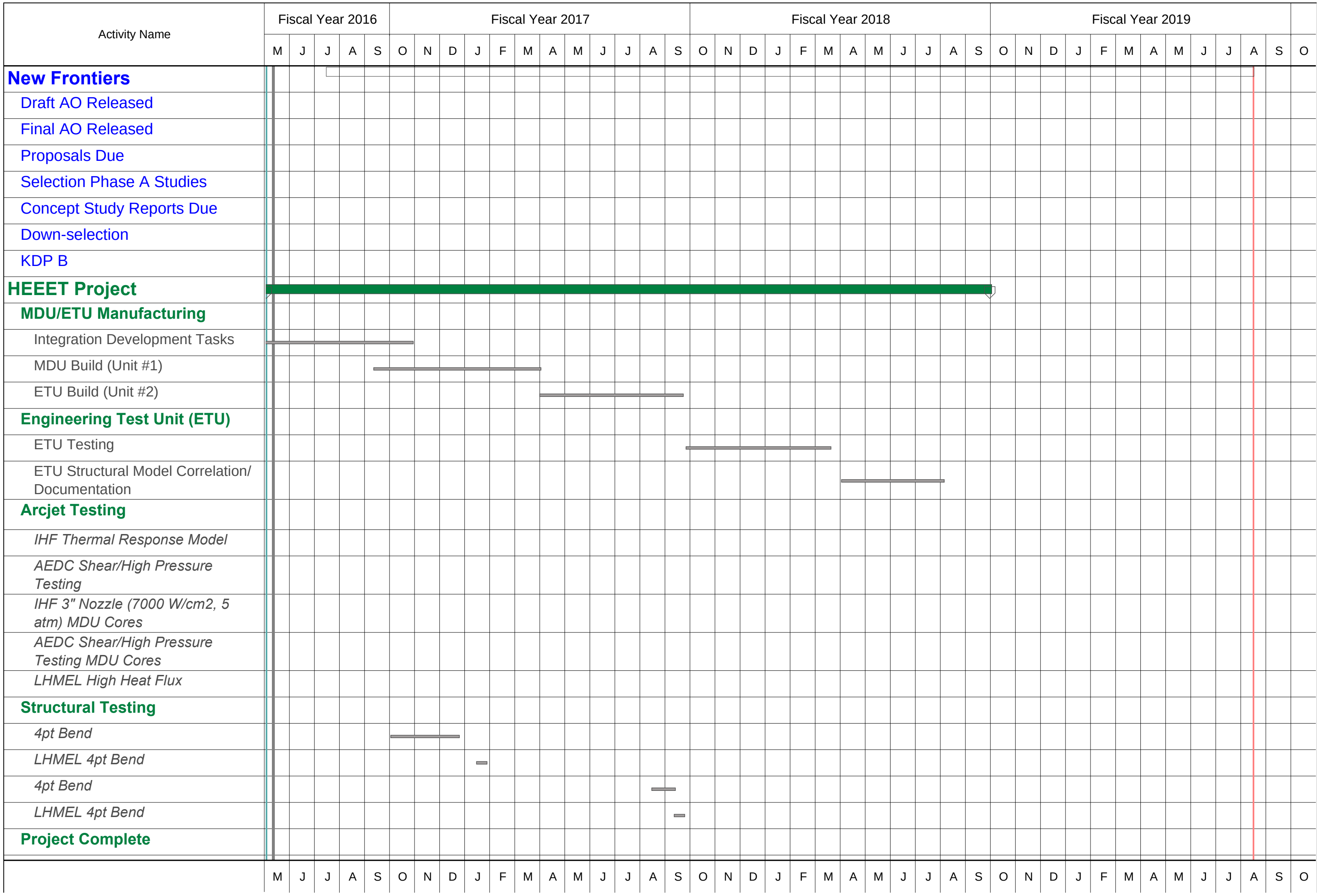
ETU In Cal-Rod Cage of T-Vac Test



ETU with Rigid Plate Closeout (Inverted)

HEEET Schedule

- **Project extension through FY18, maturation to TRL6 is prior to Phase A mission down-select and well before KDP B (~August 2019) or PDR**



HEEET Deliverables

- **Material and Process Specifications**
  - Raw materials
  - Weaving
    - 13” width x 2.1” thickness
    - 24” width x 2.1” thickness
  - Acreage Tile:
    - Forming
    - Resin Infusion
    - Machining
  - Gap Filler
  - Integration
    - 1m scale
  - NDE (CT scan)
- **Seam Design**
- **Material Property Database**
- **Thermal Response Model**
- **Sizing Study Report**
  - Saturn and Venus reference missions
- **Engineering Test Unit (ETU)**
  - ETU Test Report
- **Validated Structural Analysis Tools**
- **TRL and MRL Assessment**
- **Sustainability Assessment**
- **Maturation Plan**
  - End of HEEET to Flight
- **Assessment of remaining risks/concerns**
- **DAC Reports**
  - Saturn (~1m) specific
  - Venus (~3.5m) specific
- **Seam repair demonstration**
- **Manufacturing/integration demonstrated at 1m scale**
  - Approaches should be scaleable to larger size (however will not be demonstrated)
- **EDL flight instrumentation is outside the scope of HEEET project**

Proposal Team Responsibilities

- **Trajectory Analysis, Aeroheating (CFD), Payload and Compatible Aeroshell Sizing, Carrier Structure Design and Structure Costing, Engineering Science Instrumentation**
- **HEEET Design:**
  - HEEET team provides constraints on tile size and lessons learned from 1m MDU/ETU
- **Flight MDU/EDU and other required testing:**
  - Test Definition/Costing
  - HEEET team provides HEEET specific limited guidance on issues
- **HEEET Costing and schedule**
  - HEEET team provides background on manufacturing process, ID's sources for raw materials, vendors supporting manufacturing steps, but proposal team must negotiate directly with suppliers for detailed cost estimates and lead time and integrated schedule.
- **# of heat shields**
  - Flight + spare + EDU + MDU, etc…
  - This coupled with testing requirements etc.…will define how much woven material is required
    - Given the high cost of set-up would be advisable to set up loom only once and weave everything.
- **Proposal writing related to HEEET**

HEEET Team Responsibilities

- **Aerothermal constraints, TPS thickness constraints, TPS Sizing**
  - Constraints on trajectories based on manufacturing limitations
  - HEEET surface roughness estimates to be used by proposal team to compute roughness heating augmentation
  - HEEET Team will perform limited sizing for design trajectories
  - Guidance on margin policy for HEEET
- **Carrier Structure Guidance**
  - Seam strain level, Radius of curvature, Interface with payload, etc
  - ETU carrier design under development (Ref: Saturn Entry Probe)
- **Guidance on estimating implementation cost and schedule**
  - HEEET team will not conducted detailed cost estimates or develop implementation schedule.
  - Will provide vendors utilized for ETU build and detailed insight into integration
- **Guidance on HEEET specific implementation tasks (> TRL 6)**
- **Guidance on Risks/Challenges related to implementation of HEEET for specific proposal**
- **HEEET Implementation Credibility Review (HICR)**
  - Will review final cost, schedule and technical aspects of HEEET implementation and provide a written report
  - Not an embedded design function
- **Engineering Science Instrumentation**
  - Provide lessons learned from ground based instrumentation. ESI is outside the scope of HEEET development

Summary

- **Feasibility of HEEET Gap Filler has been demonstrated in High Heat Flux Arcjet Testing (~7000 W/cm^2 and 5 atm) and in initial structural testing**
- **HEEET manufacturing has progressed well:**
  - Weaving:
    - >125 ft of 13” wide x 2.1” thick material
    - Scale up to 24” width in progress
  - Forming/Resin Infusion/Machining:
    - FMI has modified resin infusion vessel to support HEEET infusion
    - FMI fabricated MDU tile set and demonstrated machining
- **Integration approach has been baselined and feasibility demonstrated at coupon/breadboard level**
- **1m Manufacturing Development Unit (MDU) will be completed in mid-FY17**
- **HEEET maturation on target to support New Frontiers**

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